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A STUDY OF THE DIURNAL SUMMER WIND SYSTEM AT GALVESTON, TEXAS

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ABSTRACT

An investigation of 30 days hourly wind observations at Galveston Island, Texas revealed a complex land-sea breeze system. The system is obscured by fairly constant on-shore winds resulting from the western extension of the Bermuda High as well as local effects such as the presence of water on all sides of the land area. The large differences in wind direction on the island are theorized to be due to solenoidal effects.

1. Introduction

It is known as a general fact that land and sea breezes exist along the Gulf of Mexico coastline. But there are few sea-side locations where these wind systems can be routinely studied without setting up special observing stations. One such convenient, permanent site is located on Galveston Island, Texas, just off the southeast Texas Gulf Coast. The island is approximately three miles wide by twenty-five miles long. It is separated from the mainland by a one mile strip of water. The city of Galveston is located on the northeast end of the northeast-southwest oriented island. Within the city are two permanent weather observing sites: one is located at the Galveston Weather Bureau Office (WBO) near the downtown business district; the other is located about four and one-half miles to the southwest at Scholes Field, the municipal airport. AMOS (Automatic Meteorological Observation System) equipment is in use at the latter site to observe, code and transmit hourly aviation weather. The island terrain is fairly level with the highest point being eighteen feet above mean sea level.

A comparison of the observed winds at AMOS and WBO was made during the thirty days from 28 July to 26 August, 1965. The purpose of this study was to determine three things:

(1) if a summertime land-sea breeze wind system can be recognized near the surface of the island; (2) if there is a diurnal pattern to these wind changes; and (3) if such a diurnal wind system has equal effects at AMOS and WBO.

2. Wind Sensors

Identical wind sensors are used at both sites. Wind speeds are measured by Friez Instrument model F420-C. This is a three-cup anemometer having a starting speed of two miles per hour and a selective scale range of from

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2 to 100 mph or to 200 mph if desired. Wind directions are measured by Friez Instrument model F420-D "arrow" type wind vanes oriented to true north. All equipment is maintained by Galveston WBO Electronic Technicians.

The WBO sensors are atop the Galveston City Hall, one block south of the WBO. The equipment is 105 feet above ground level. There are no major obstructions within 200 feet horizontally; however, there is a tall structural antennae tower about twenty feet east of the sensors. With prevailing southerly winds, the tower has little effect on the sensors.

The downtown site is 4800 feet from the Gulf of Mexico and 14,000 feet from the bay. The entire area around the City Hall, and from there to the beach, is densely populated with two and three story residential and business buildings. In contrast, the instruments at Scholes Field stand in the center of the airport, 23 feet above ground level. The site is 7200 feet from the Gulf and 8200 feet from the bay. These distances were measured along the track of the prevailing wind directions.

3. Data

Data of wind speed and direction were collected for thirty days from 28 July to 26 August, 1965. This particular time interval was chosen because it was felt that maximum heating over the land during late July and August would produce the greatest potential for development of a recognizable diurnal wind system.

The information was collected on an hourly basis. AMOS wind data was recorded directly from aviation weather sequences as received in the Weather Bureau Office. Weather Bureau employees made a one-minute average of the wind speed and direction shortly before each hour. Wind direction was recorded to the nearest ten degrees from north, while wind speed was noted to the nearest mile per hour.

4. Assumptions

Four assumptions were needed to simplify the working of the data into a meaningful form: (1) It was necessary to assume that each pair of AMOS and WBO observations was made at the same time. This assumption made it possible to compare the observations on a time constant basis. In reality, AMOS observations were made at from one to five minutes before the hour while WBO observations were made at from five to ten minutes before the hour. (2) Since the anemometers have a starting speed of two miles per hour, all wind speeds of 2 mph or less were assumed to be calm. These low speeds were not used in computations. (3) Wind directions at speeds of two miles per hour or less were assumed to be indefinite and were omitted from computations. (4) Wind direction of due north was assumed to be 0 degrees in all computations.

5. Computations and Results

The observed data was analyzed in three ways: (1) by a daily basis for the thirty days, (2) by an hourly basis from the summation of the thirty days observations and, (3) by the wind vectors from the summation of the hourly observations.

Daily basis. The daily average wind direction at each site was computed using the formula:

$$\overline{X} = \Sigma X/N = \text{average} \tag{1}$$

where: ΣX is the summation of individual observations,
N is the number of observations.[1]

Fig. 1, Daily Average Wind Speed shows the results of computations for thirty days data. The largest average difference computed was about 1.5 miles per hour. On most days the average wind speed varied less than one mile per hour between AMOS and WBO. Differences in average wind speed were greatest at higher wind speeds. This is due to the performance of the cup anemometer. Cup anemometers frequently register as much as ten per cent high in gusty winds because the cups are able to accelerate faster than they decelerate. Gusty winds are most evident at AMOS due to surface-friction induced turbulence. Therefore the wind speed would be shown higher than actual when relatively stronger winds produce greater surface turbulence. Personal observation pointed that the variability of wind speed increased with speed at both sites. However, since the differences between AMOS and WBO were small, it was estimated that wind speed variability is equally small.

The t - test of statistical inference was used to be more certain that the wind speed averages are identical and that the differences are negligible. The form of the test used was:

$$t = (\overline{d} - 0)(S^2/N)^{-\frac{1}{2}} \tag{2}$$

where d is the difference in each hourly wind speed between AMOS and WBO[2], $\overline{d}$ is analogous to $\overline{X}$ in formula (1). N is the number of paired observations. S^2 is the variance of the wind speed as found by the formula:

$$S^2 = \Sigma(d - \overline{d})^2 / (N-1) \tag{3}$$

t is a measure of the distribution of the observed differences compared to the differences in a "normal" set of observations, i.e., observations in which differences exist solely by chance variations in the wind.

...1 N was not always equal to 24. Assumptions (2) and (3) above were applied on 13 of 30 days.

...2 The paired difference, d, is used to eliminate extraneous non-random elements which may bias the results, e.g., rounding errors and errors due to differences in the times of observations.

Figure 1

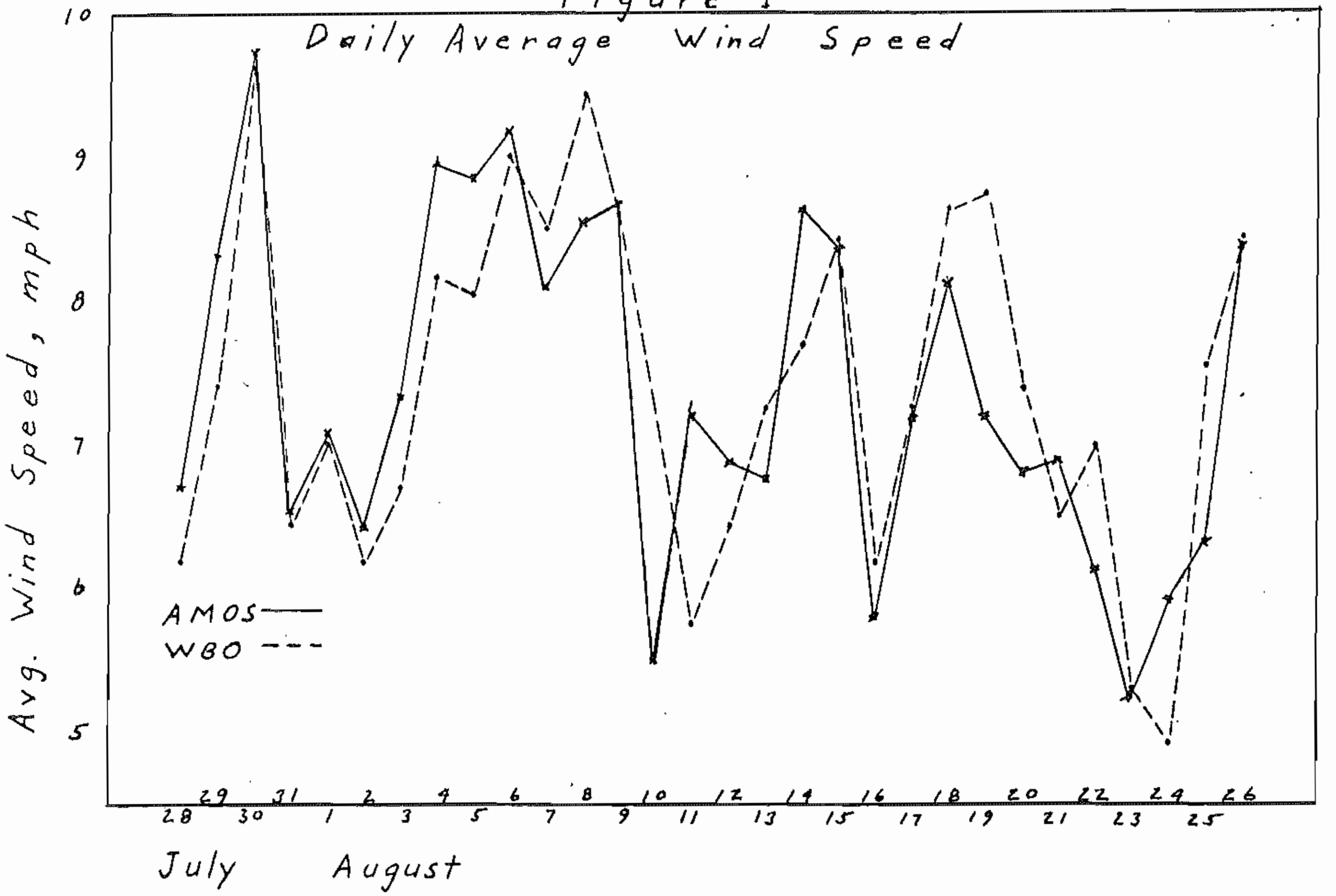
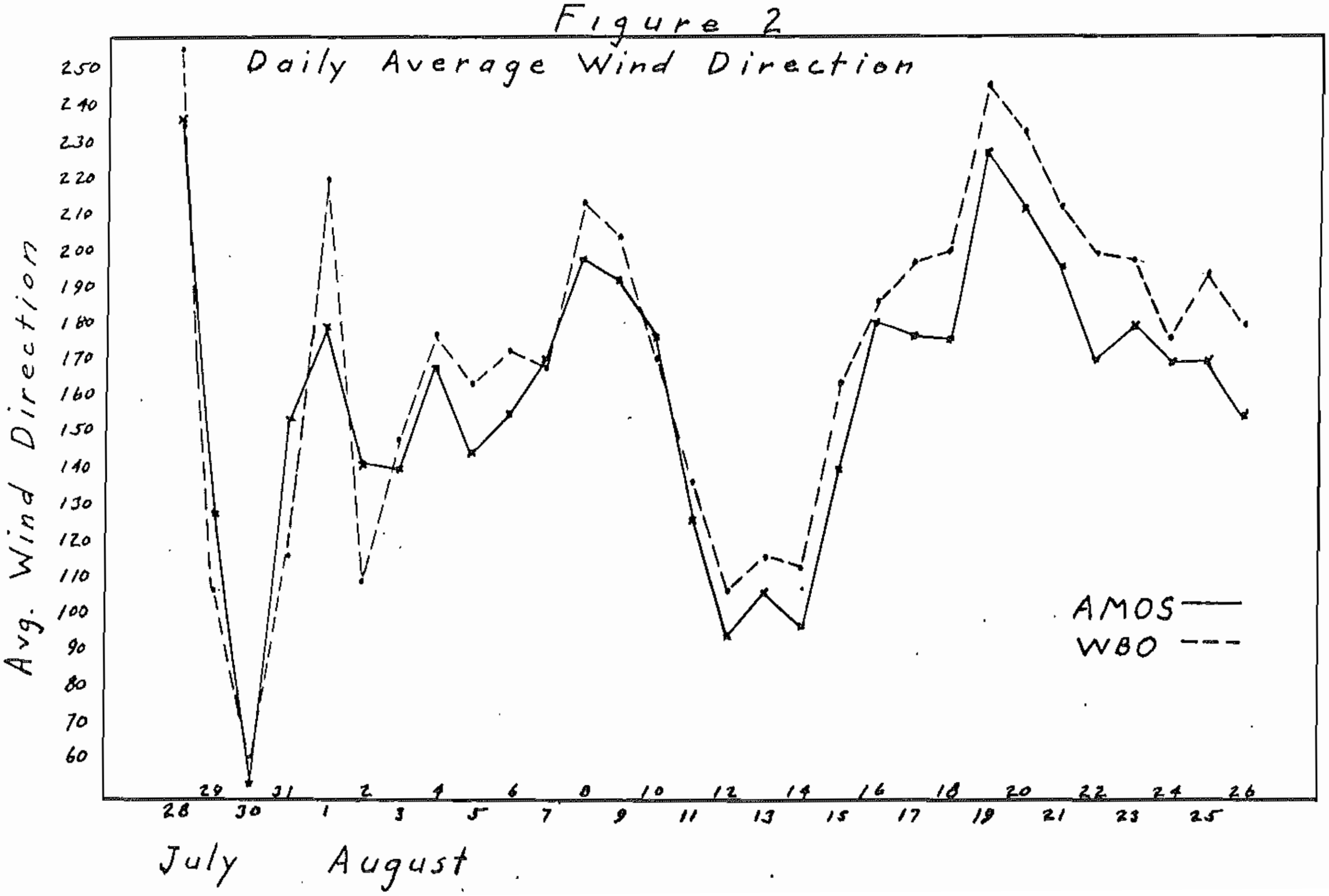


Figure 2



A significance level, α , of 0.01 was used for comparison, where α is the probability that a difference will be computed to be 0 when such a difference does exist. The lower the value of α, the more certain it is that the differences are negligible.

This test was used on the individual daily observations as well as on the thirty day totals. The results were identical; namely, there is no significant difference between the wind speeds observed at AMOS and WBO.

Fig. 2 shows the Daily Average Wind Directions (computed by equation (1)) at AMOS and WBO. On twenty-five of thirty days the average observed wind at WBO blew from the left (according to Buys-Ballots Law) of that at AMOS. During the early days of observations the averages were nearly equal. As the study continued the WBO direction increased in a clockwise direction until it was consistently to the left of AMOS by ten or more degrees per day. For the thirty days the wind at the downtown site was found to blow from a direction averaging more than sixteen degrees to the left (with back to the wind) of that at the airport.

The t-test of statistical inference using equations (1), (2), and (3) was applied to the data. It was found that for similar circumstances, in ninety-nine cases out of one hundred the wind direction at WBO would blow from the left of that at AMOS.

Hourly basis. More interesting results were found when the data was averaged on an hourly basis for the entire thirty days. The wind speed and direction averages for each hour are plotted in Figs. 3 and 4.

Fig. 3 shows clearly that a diurnal variation in wind speed did exist at Galveston during the time of the study. The average of observed wind speeds at both stations increased from about 6 mph in the early morning to about 9 mph by early afternoon. Speed changes were fairly uniform at both sites. The dynamic forces which caused this cycle apparently affected both stations equally.

The hourly direction averages for each hour of thirty days data are summarized in Fig. 4. The differences in wind direction between AMOS and WBO are clearly seen. Fig. 5 shows the wind speed and direction differences obtained on a twenty-four hour basis. There is a much more recognizable diurnal tendency in direction than in speed. During the early morning hours when speed is at a minimum, direction is generally from the south. A relatively sharp change in direction occurs about 1 P.M. with the wind continuing to change to a more southeasterly direction throughout the afternoon. Direction returns to a southerly flow after 6 P.M.

Figure 4

Diurnal Direction Variation

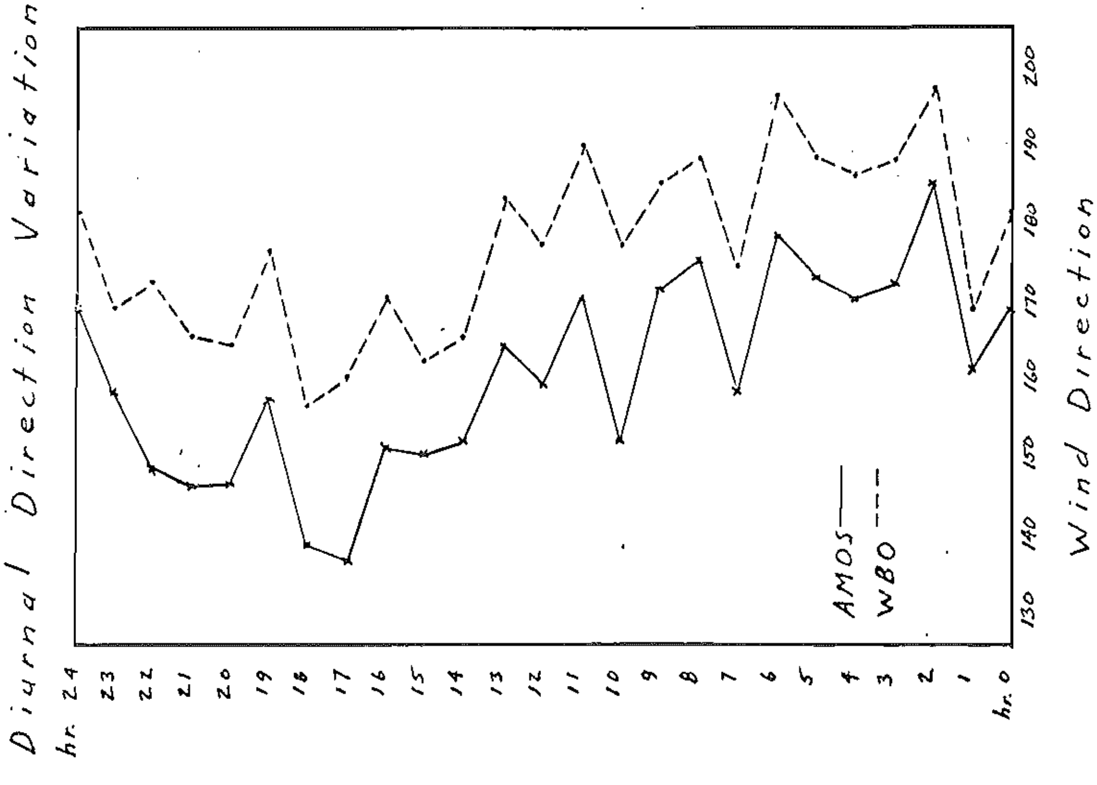


Figure 3

Diurnal Speed Variation

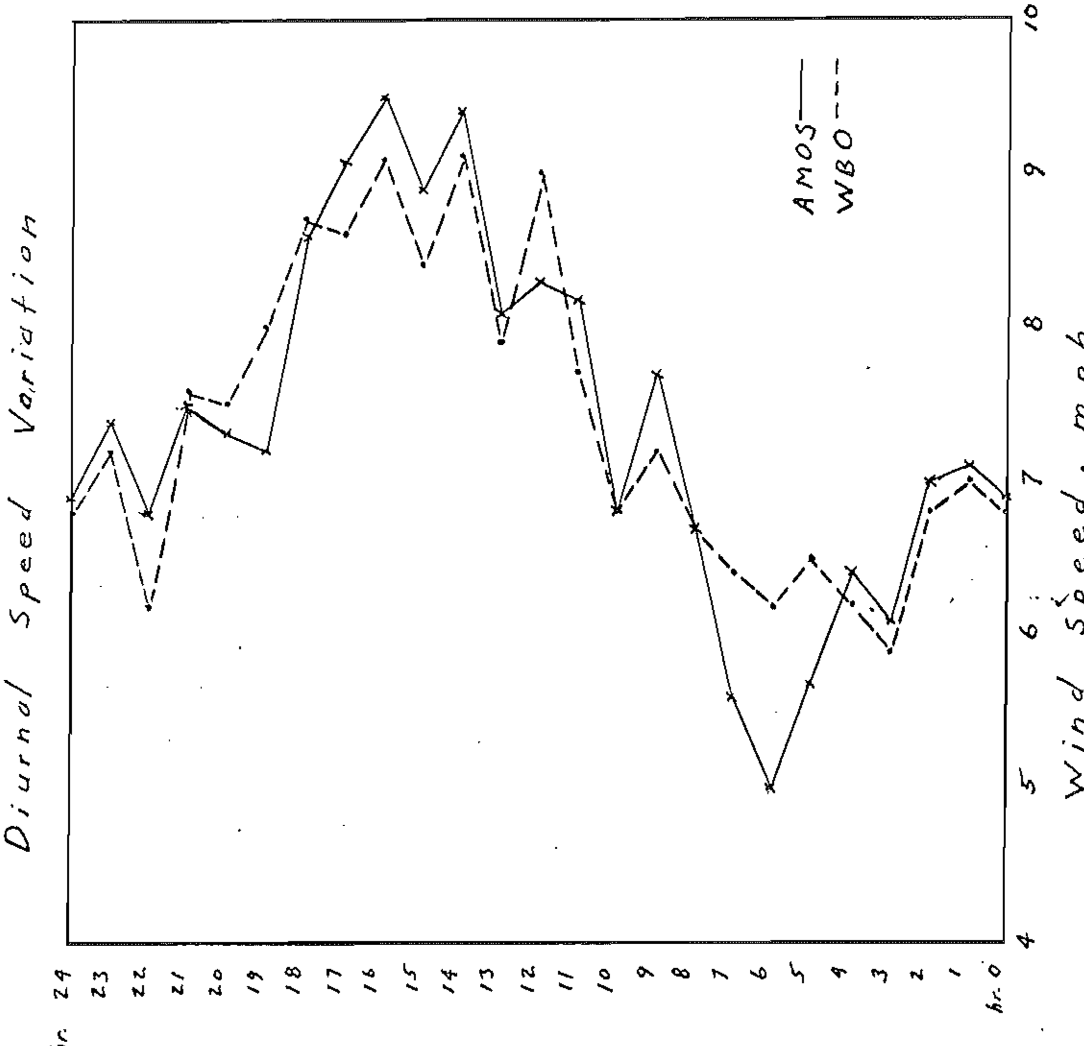
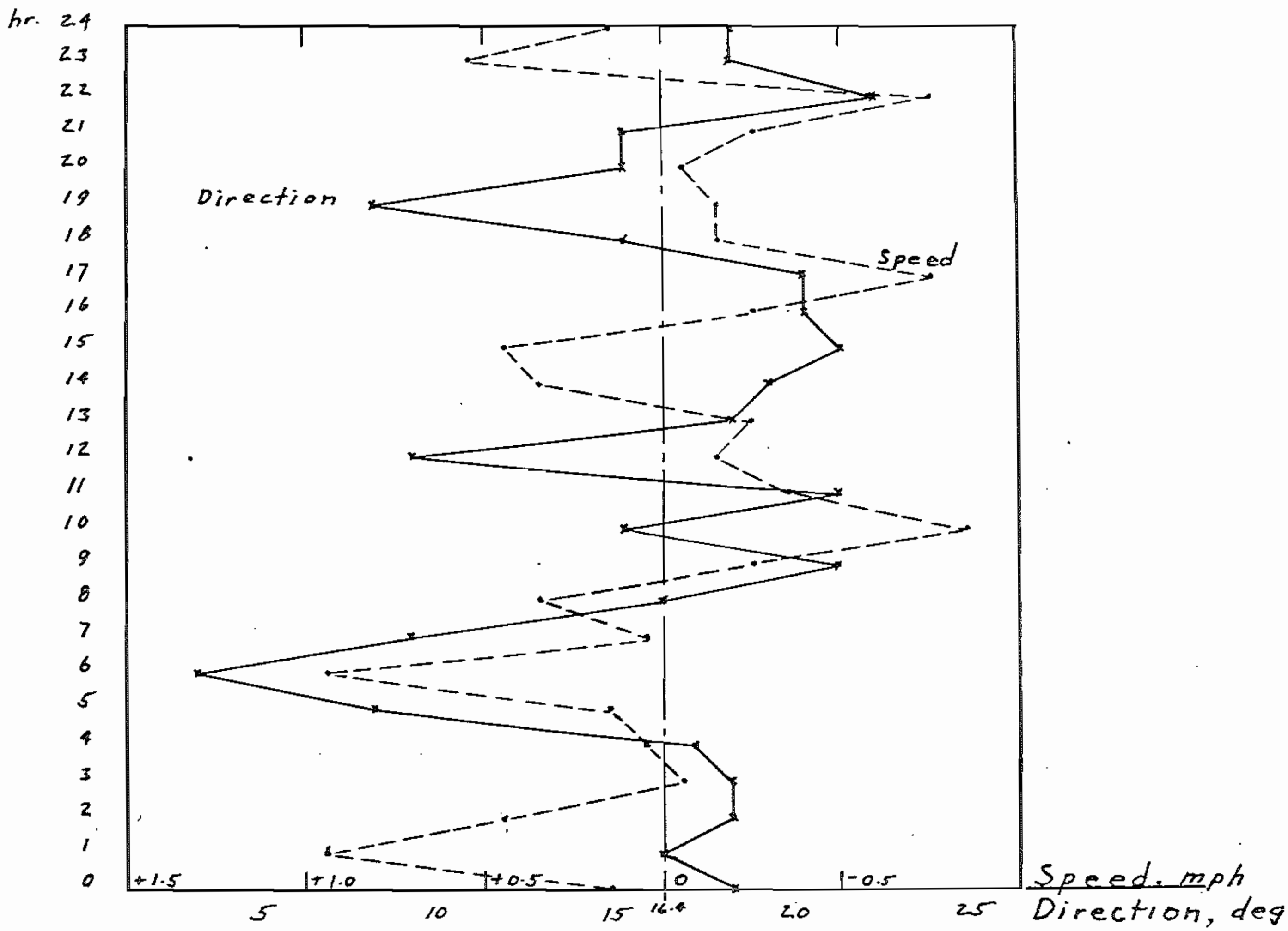


Figure 5

Wind Differences AMOS-WBO



Vector basis. Separating the component vectors and applying the t-test yielded much the same results as in the previous cases. However, the component vectors give more information for the explanation of the wind differences on the island.

The southerly component differences were computed to be significant only at the .20 level. This does not give enough assurance to conclude that the southerly wind components were different at AMOS and WBO. Fig. 6 pictures the southerly vectors at each site. The vectors appear to be similar except during the late afternoon when the wind direction at both sites was shifting to a more easterly direction.

In contrast, the easterly components were found to be significantly different at the .005 level. These vectors increased throughout the day, reaching a maximum by late afternoon. The east component is in all cases smaller than the corresponding hourly south component. This is seen easily in Fig. 7.

The local bay and island effects are most recognizable in the east vectors. During the early morning a slight west vector appears at WBO while AMOS to the south maintains an east vector. Thus there exists a slight anticyclonic tendency over northern Galveston Island as would be expected, as the land area cools relative to the water. The anticyclonic tendency disappears early in the day and by late afternoon a cyclonic regime exists as the land is heated to its maximum.

6. Explanations

It might have been expected to find greater diurnal variation in the winds at Galveston. I believe an explanation can be given which will confirm the existence of a land-sea breeze system which would be more obvious if overriding factors were not present.

Galveston Island is about three miles wide at the observation sites. There is a one mile strip of water, Galveston Bay, separating that part of the island from the mainland. This water area exerts a force to set up a daytime wind flow from water to land which is in direct opposition to the same forces on the Gulf of Mexico side. The bay forces tend to restrict the larger Gulf influences. As a result, both wind speed and direction show less variation than if the bay were not present.

Galveston Bay influences the flow to a small degree compared to the influence of the Bermuda High. The Bermuda High produces prevailing onshore winds in the West Gulf throughout the summer. Flow induced by the High gives Galveston generally steady southerly winds both night and day, as seen by Fig. 7 in particular. The Bermuda High effectively swamps local effects. If the High were not present it might be expected that winds would more closely match a classic sea-land breeze system. Wind speeds would be perhaps one-half of those observed in the presence of the High. Wind directions would exhibit full 180 degree shifts in twenty-four hour periods during the summer.

Figure 6

N-S Wind Vectors
(s coded positive)

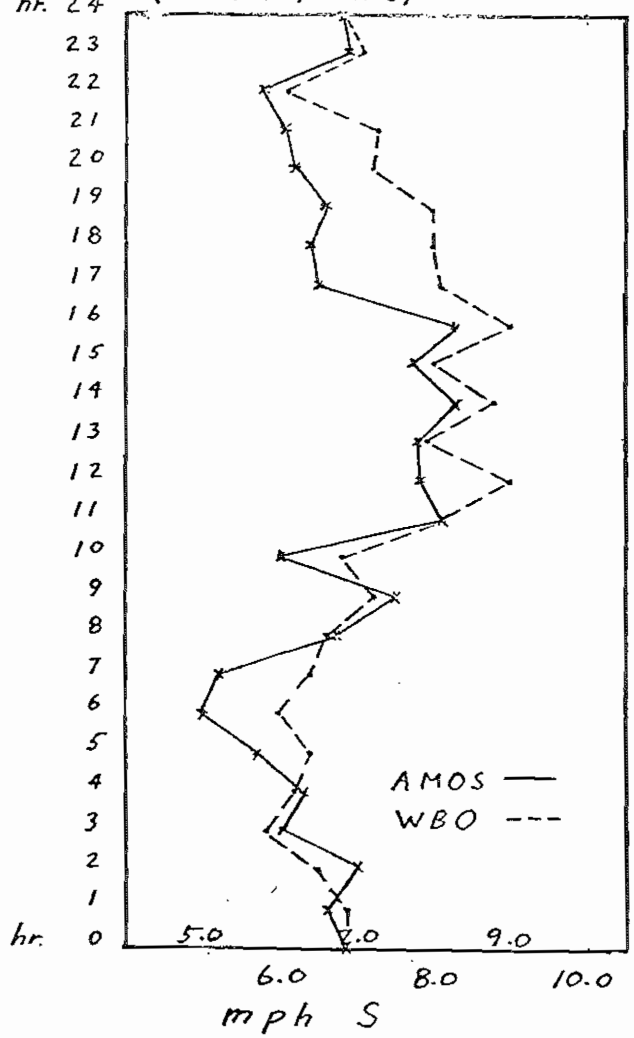
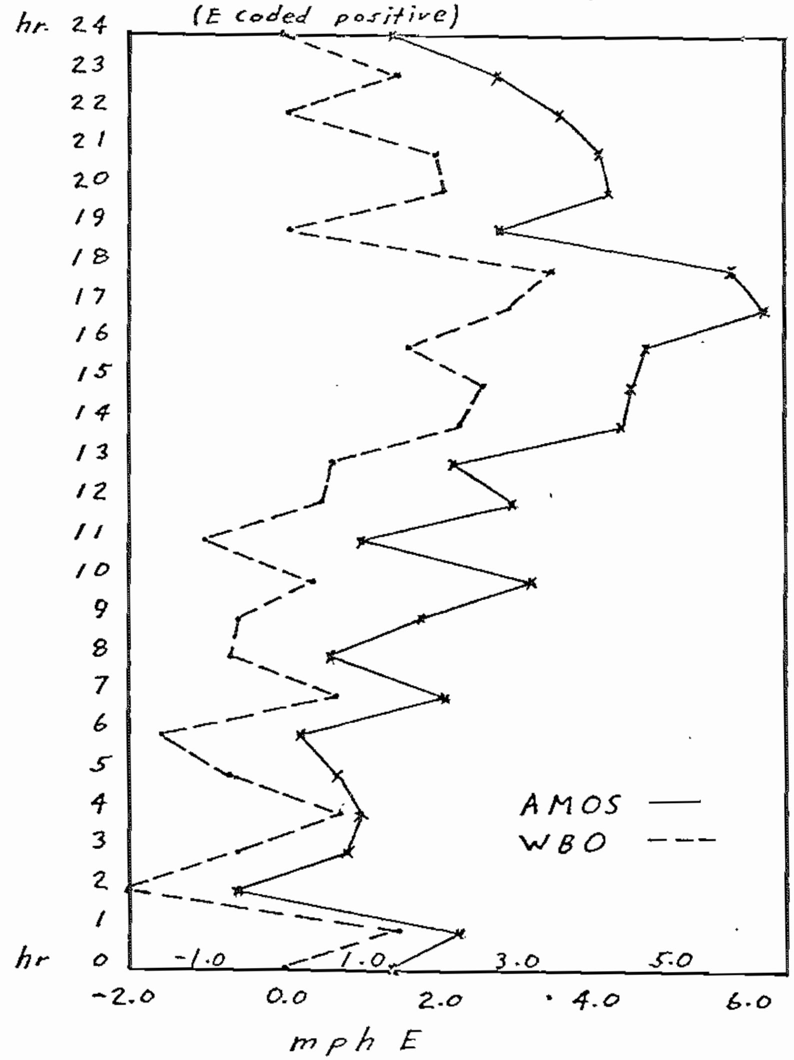


Figure 7

E-W Wind Vectors
(E coded positive)



The difference in wind direction between AMOS and WBO can be explained as the results of solenoid effects associated with the local and prevailing wind systems. The Weather Bureau Office is about mid-way between the Gulf and Galveston Bay. AMOS is about one-third the distance from the Gulf to the bay. According to the solenoid theory, air flowing from the Gulf would be deflected to the right as it passes over the land. Since the WBO site is more inland than the AMOS site, the solenoid effect would predict that the WBO wind would blow from the left of that at the airport. This is the observed condition.

7. Summary and Conclusions

There are several types of errors possible in a simple study such as this. Errors due to observational procedures, anemometer cup acceleration, time differences of observations, averaging the data, and turbulent flow are hopefully diminished (but never eliminated) by having a large number of observations and then by pairing the data for use in statistical analysis.

It has been found that a land-sea breeze system does exist at Galveston This system is limited by (1) local effects arising mainly from the presence of water on all sides of the island; (2) the Bermuda High which overrides much of the diurnal heating and cooling effects. The wind system follows a pattern of light southerly during the night and early morning, and moderate southeasterly winds during the afternoon hours. The observed wind system is different at both stations. A solenoid effect produces a more clockwise wind direction at WBO. There is little measurable difference in wind speed between the two sites.

REFERENCES

Byers, H. R., 1944: General Meteorology. New York, McGraw-Hill, pp. 82-83

Dixon, W. J., Massey, F. J., 1957: Introduction to Statistical Analysis. New York, McGraw-Hill pp. 112-127

Donn, William L.; 1946: Meteorology. New York, McGraw-Hill, pp. 172-176

Eddy, Amos, 1966: "The Texas Coast Sea-Breeze: A Pilot Study". Weather, 21, pp. 162-170.

Fisher, E. L., 1960: "An Observational Study of the Sea-Breeze". J. Met., 17, pp. 645-660.

Haurwitz, Bernard, 1941: Dynamic Meteorology. New York, McGraw-Hill, pp. 213-215.

Hess, Seymour L., 1959: Introduction to Theoretical Meteorology. New York, Henry Holt, pp. 177, 244-246, 269-271.

Middleton, W.E.K., Spilhaus, A.F., 1953: Meteorological Instruments. Toronto, University of Toronto Press, pp. 146-147.

Munn, R. E., 1964: "Turbulence Statistics at Douglas Point", J. Appl. Meteor., 6. pp. 771-779

Weatherwatch. Wwise, 18, pp. 226-231.